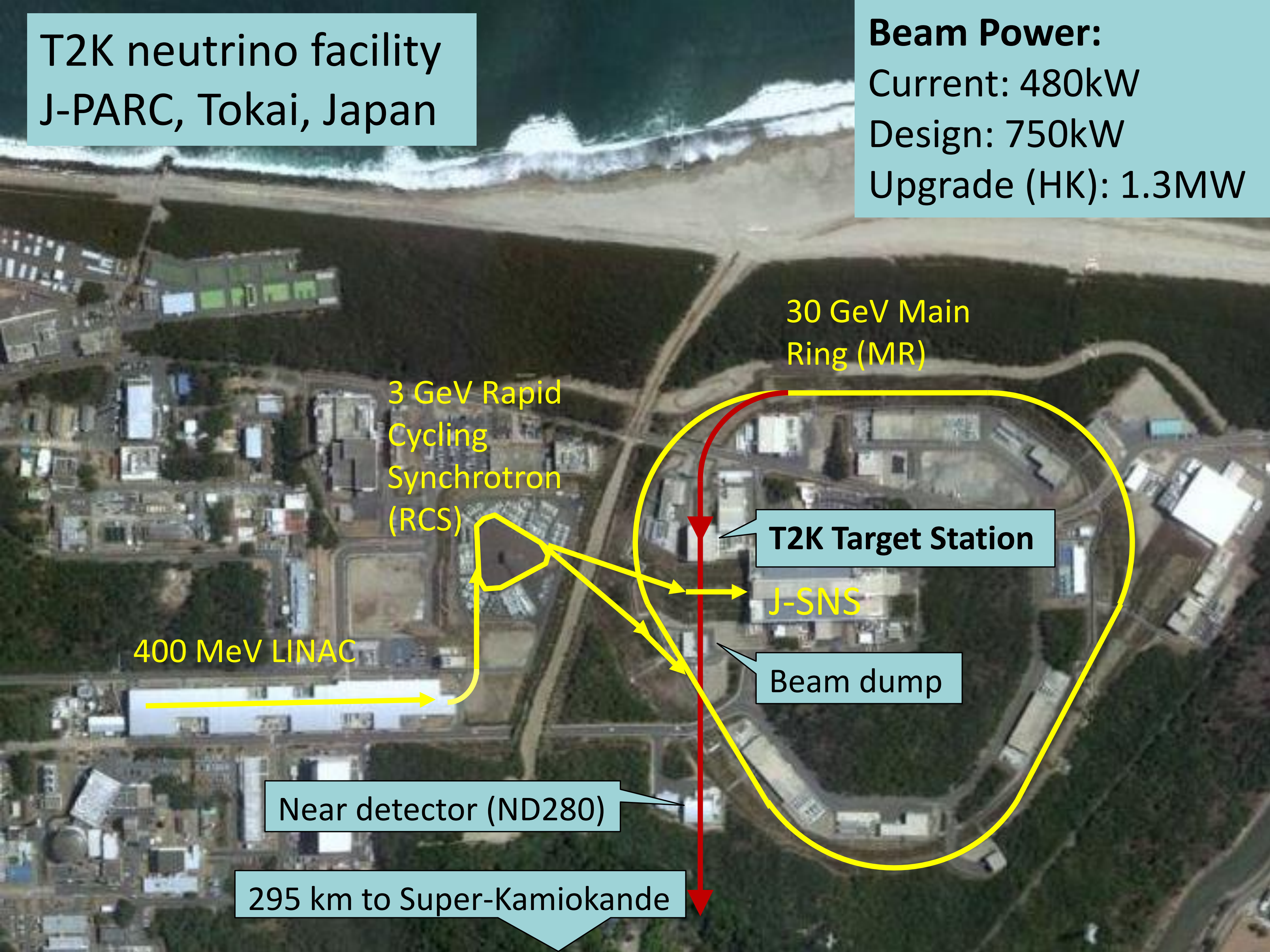
R&D Towards a 1.3MW T2K Target

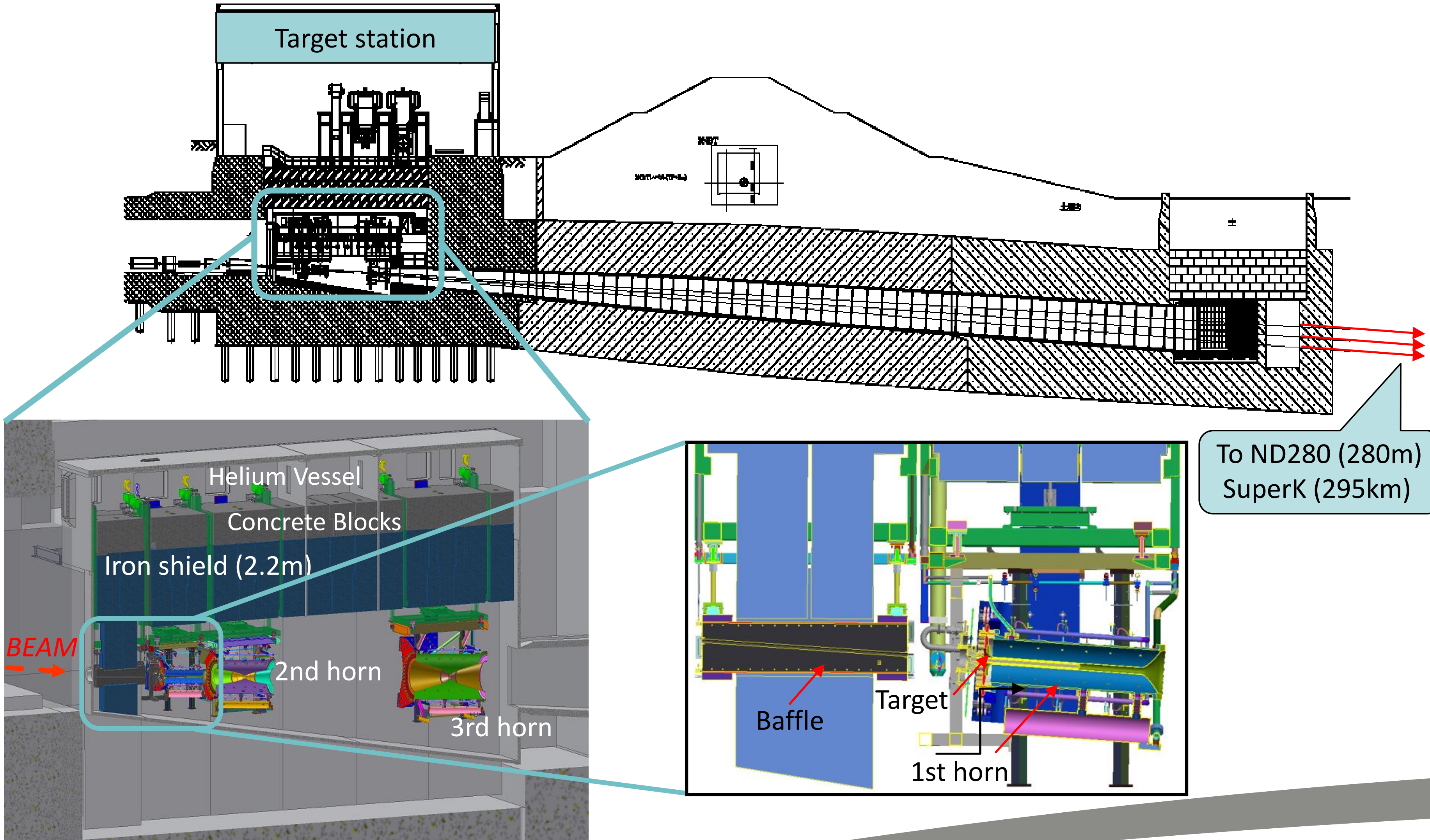
Eric Harvey-Fishenden, Chris Densham, Mike Fitton, Geoff Burton,
(High Power Targets STFC RAL)

In conjunction with the KEK Neutrino Beam Group

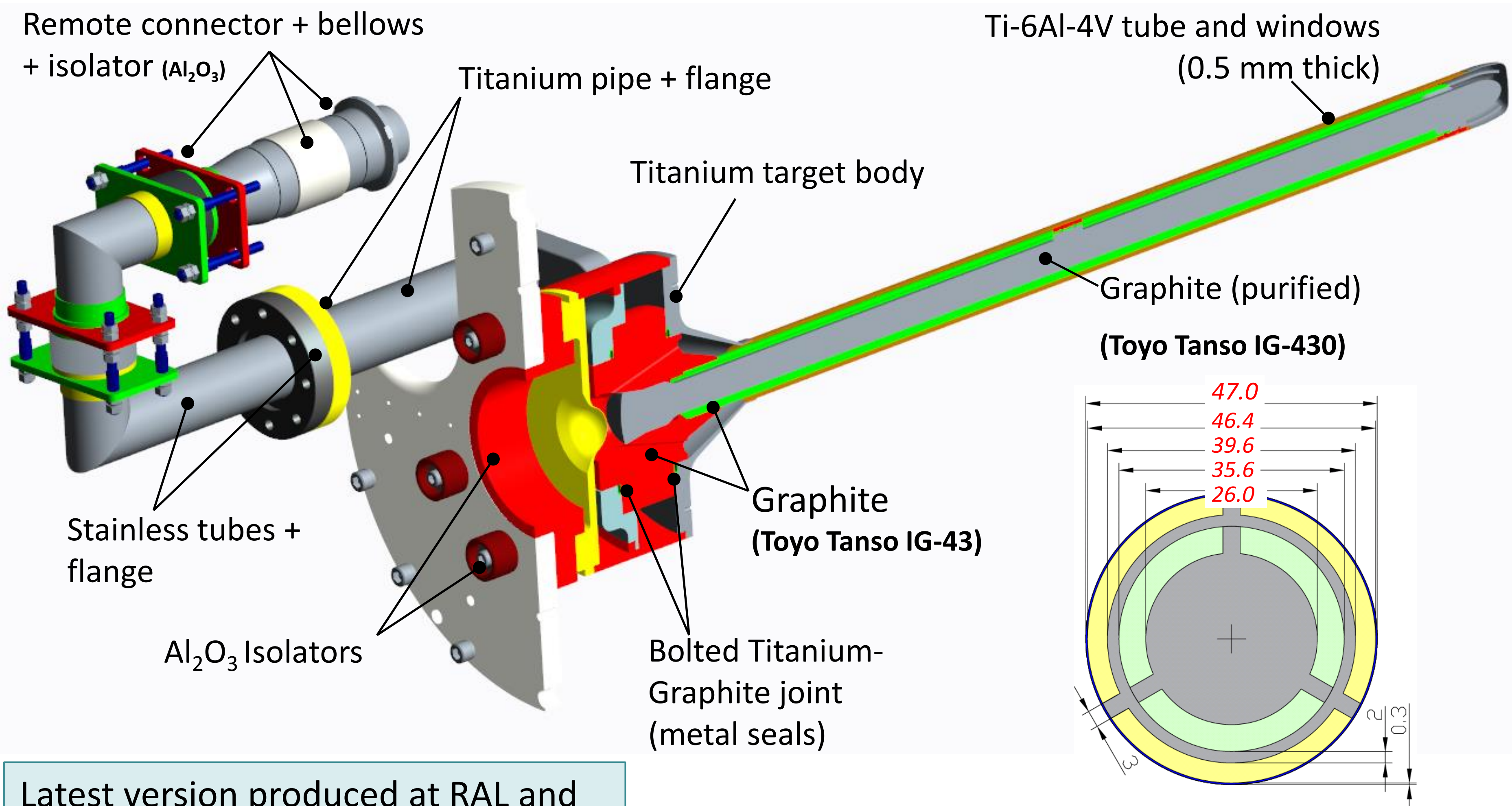
NBI 2019 Fermilab


T2K neutrino facility
J-PARC, Tokai, Japan
Beam Power:
Current: 480kW
Design: 750kW
Upgrade (HK): 1.3MW
30 GeV Main
Ring (MR)
3 GeV Rapid
Cycling
Synchrotron
(RCS)
T2K Target Station
J-SNS
400 MeV LINAC
Beam dump
Near detector (ND280)
295 km to Super-Kamiokande

Secondary Beam-line & Target Station



T2K Target



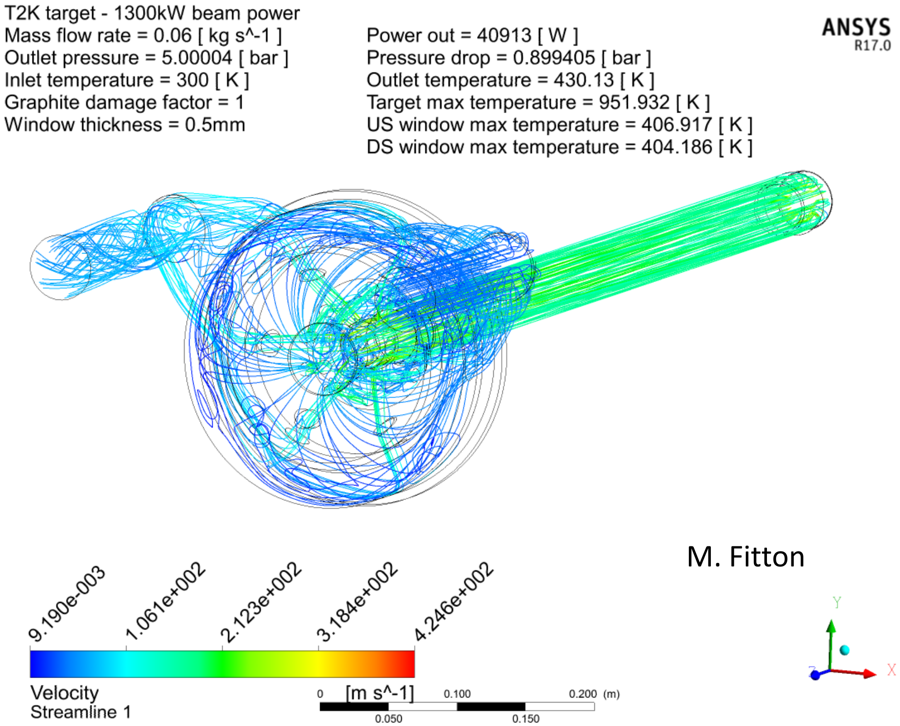
Latest version produced at RAL and shipped to JPARC late 2018, suitable for beam operation up to 750kW

Upgrade to 1.3MW (overview)

- Current operational experience up to 480kW (0.48MW)
- Beam power 0.75→1.3MW will increase the integrated heat load on the target
- Can't just increase flowrate
  - Pressure drop
  - Helium velocity
- Increase operating pressure:
  - Allows higher mass flow rate without big increase in dP or velocities
  - Compressor will be smaller, and cheaper to purchase and operate (less power consumed)

Target components must be: re-designed/optimised for operation at 5 bar, and pressure tested at 7.5 bar

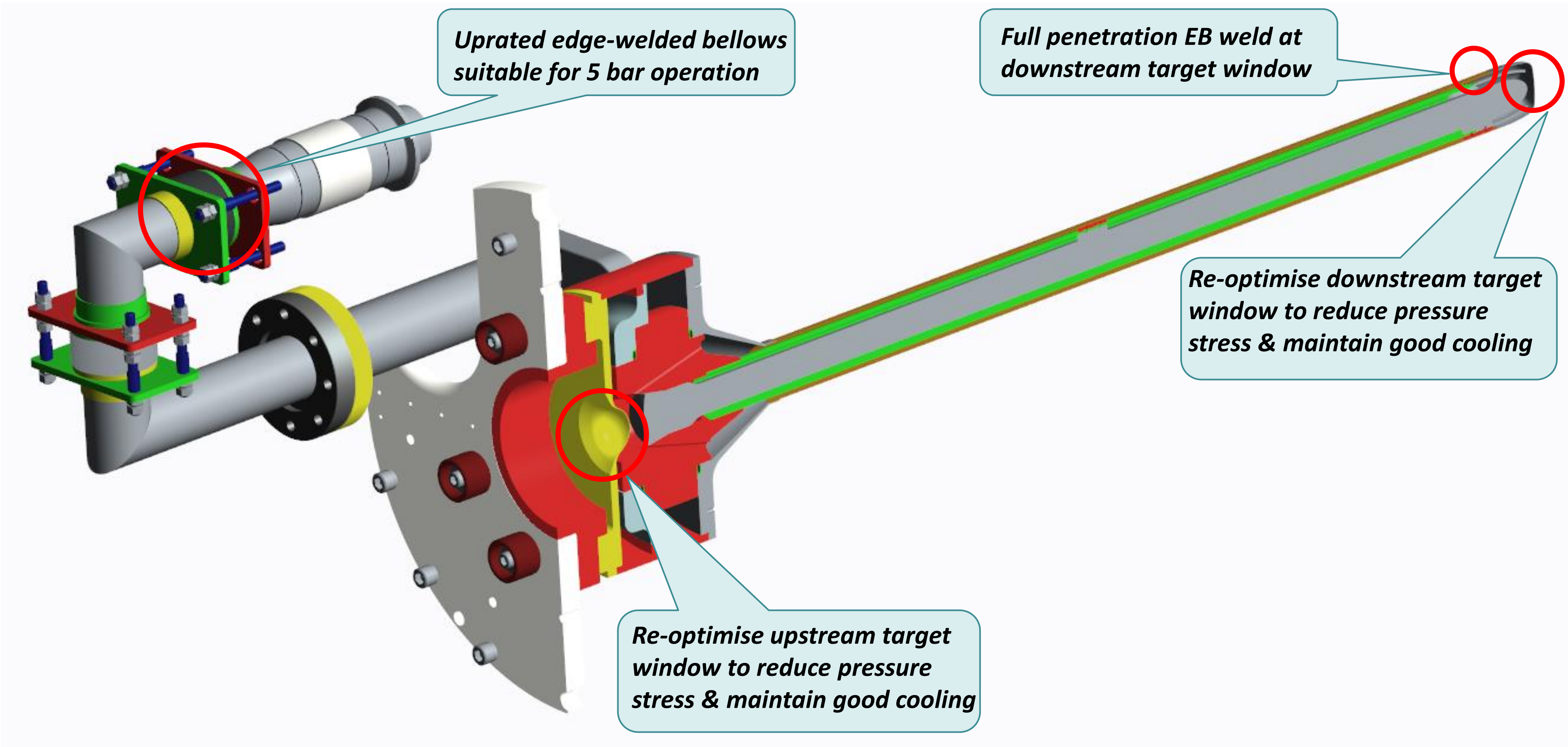
60g/s @ 5.9bar (5barG outlet) – 1.3MW beam power (Scaled MARS heat input from c. 2006)



M. Fitton

With outlet pressure @5 barG the pressure drop of the system become comparable to the 750kW design (32g/s @1.6bar/0.9barG outlet)

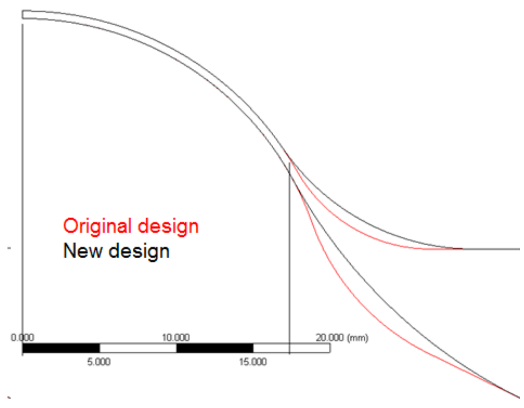
Target Upgrades for Higher Pressure

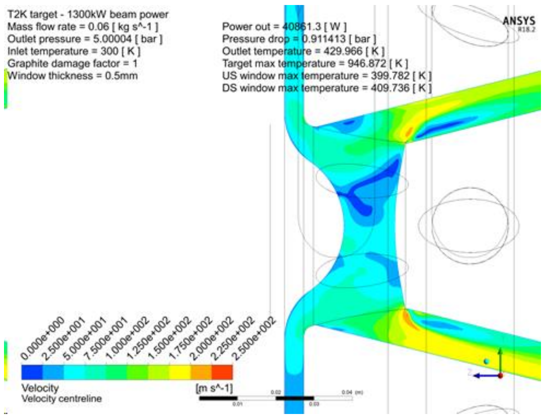


Target Windows Optimisation

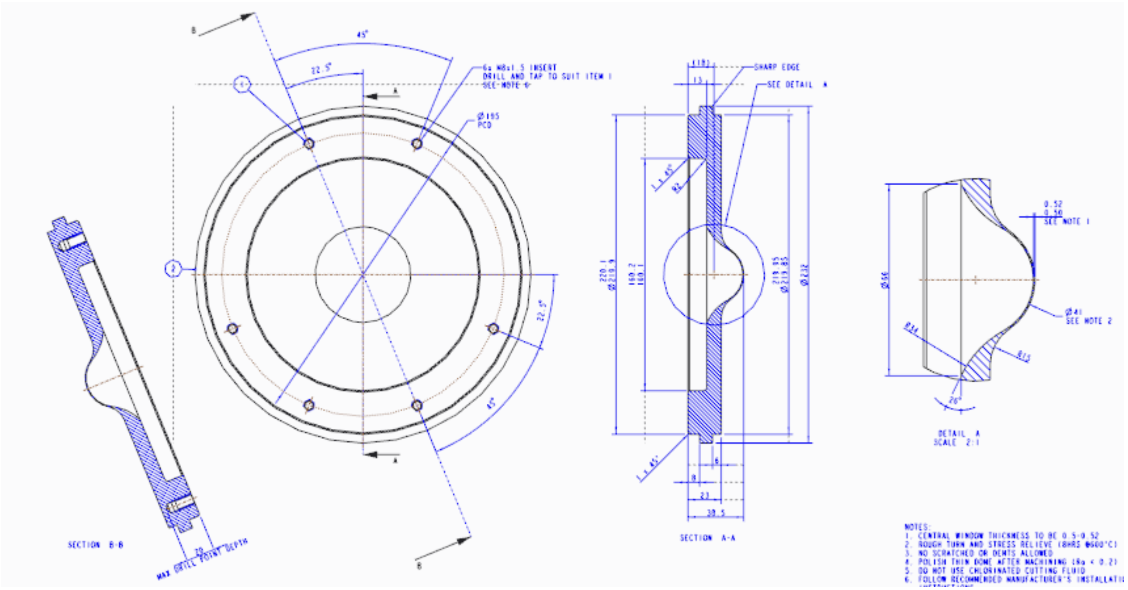
Upstream Window:

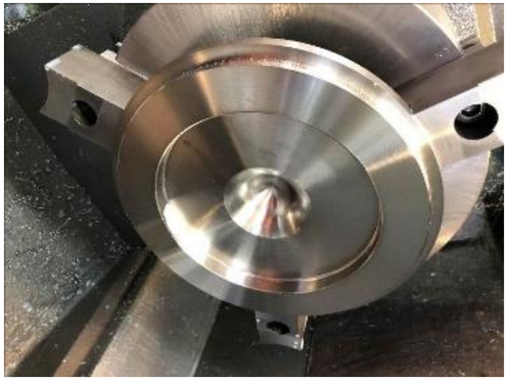
- Plate thickness increased
- Window profile maintained the same up to R18mm – off centre beams
- Blend radii increased
- Stress reduced from 74MPa →38MPa
- CFD shows modifications have little effect on flow/cooling





ANSYS plots: Mike Fitton



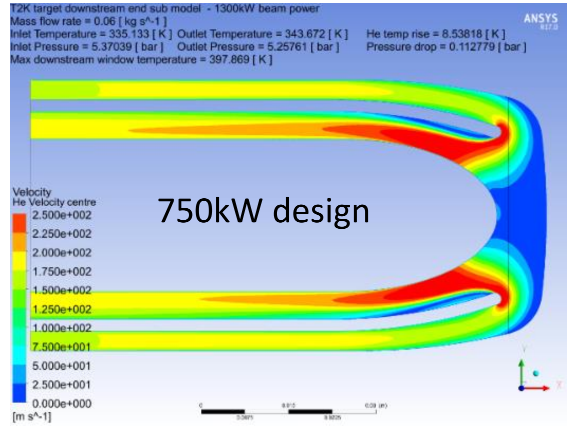


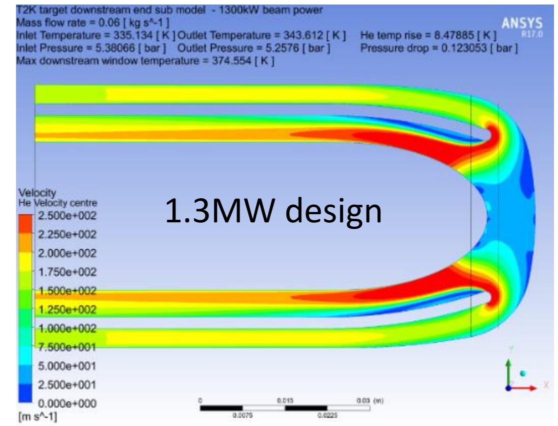
Prototype currently in manufacture

Target Windows Optimisation

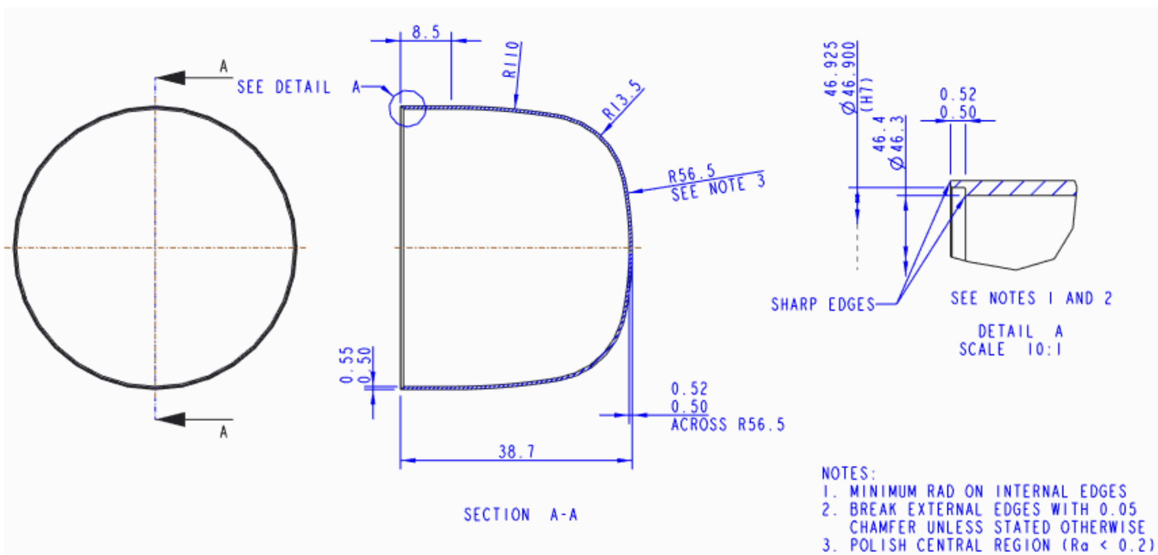
Downstream Window:

- Curvature of window increased (both at edges and on beam centre)
- Pressure stress reduced by a factor of 3
- Small (0.01bar) increase in pressure drop but small increase in cooling (6% temperature reduction)





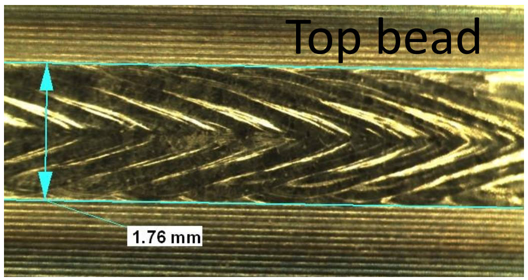
ANSYS plots: Mike Fitton

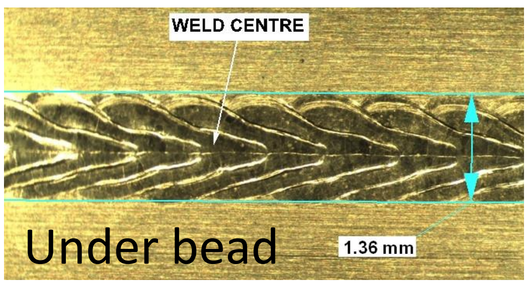


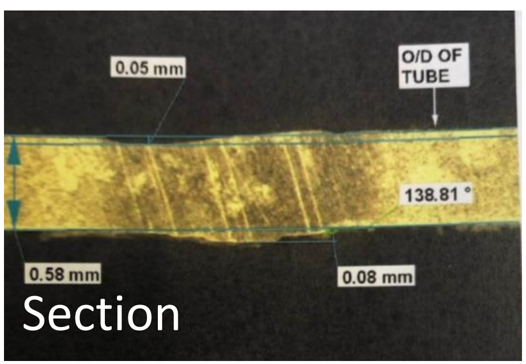
Prototype currently in manufacture

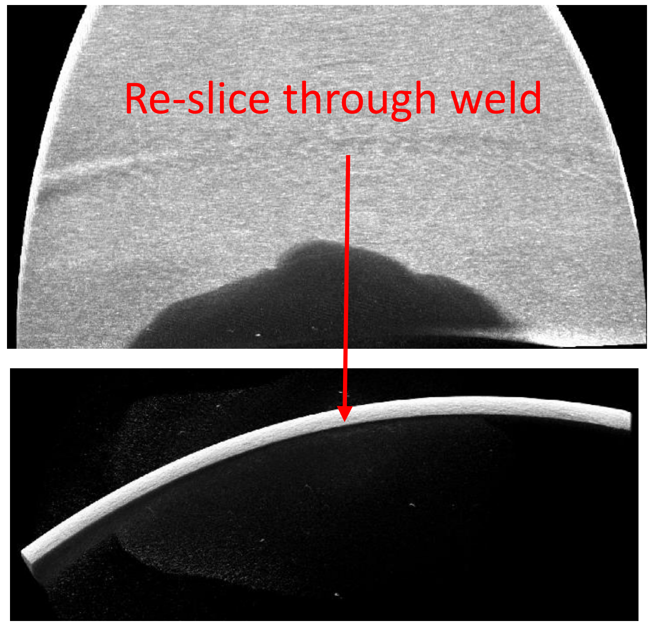
Downstream Window EB Weld Development

- Current design has just 0.25mm penetration – for higher pressure we would like a full penetration weld
- Joint prep is consumed in the weld – if the fit is not very good, the weld will contain voids or lack fill – QA is very important

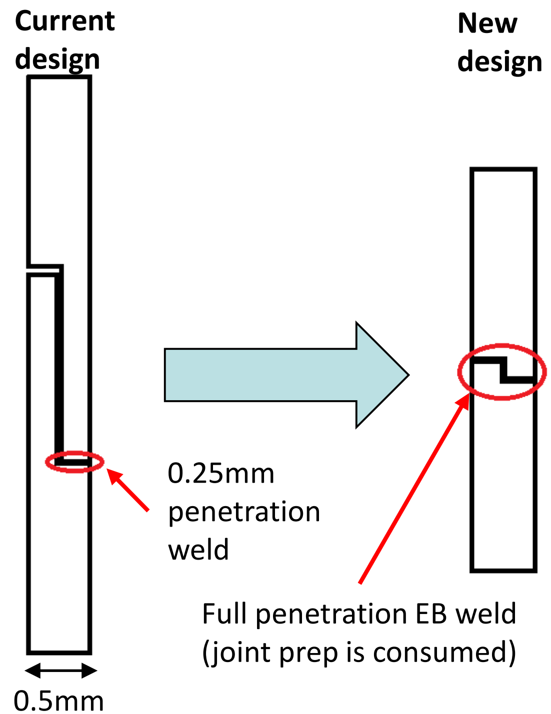


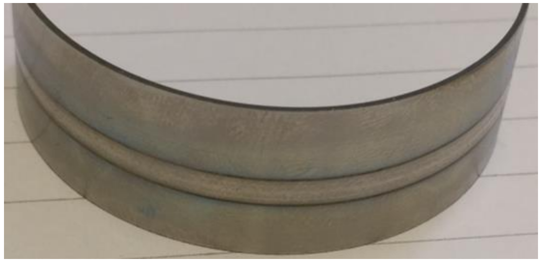






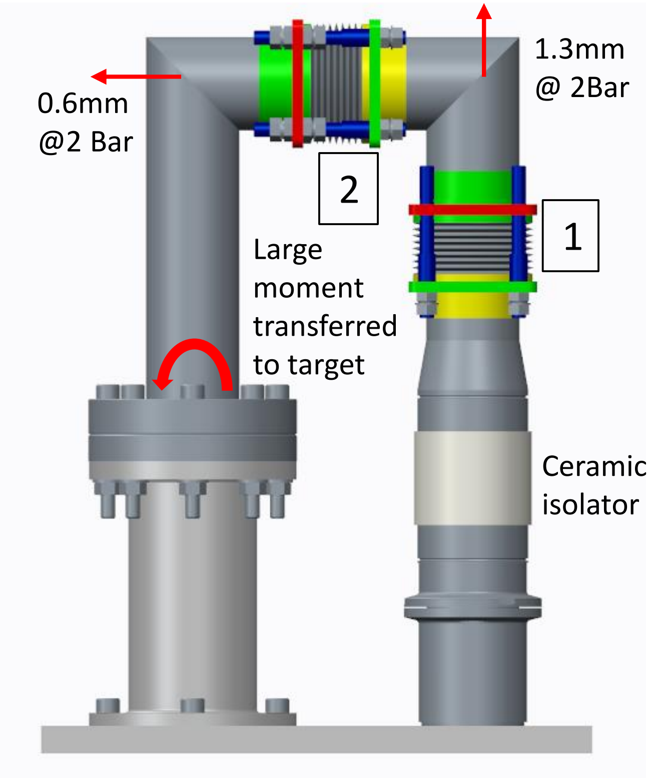
Visual inspection, cut section, dye pen & CT scan all look good – no visible pores or defects





High Pressure Target Pipes

- 5 Bar capable edge-welded bellows have been sourced and a prototype target He pipe produced
- Bellows protect fragile ceramic (more on this later)
- Low pressure testing revealed that a re-design is required
  - Expansion of free bellows "1" under pressure is excessive

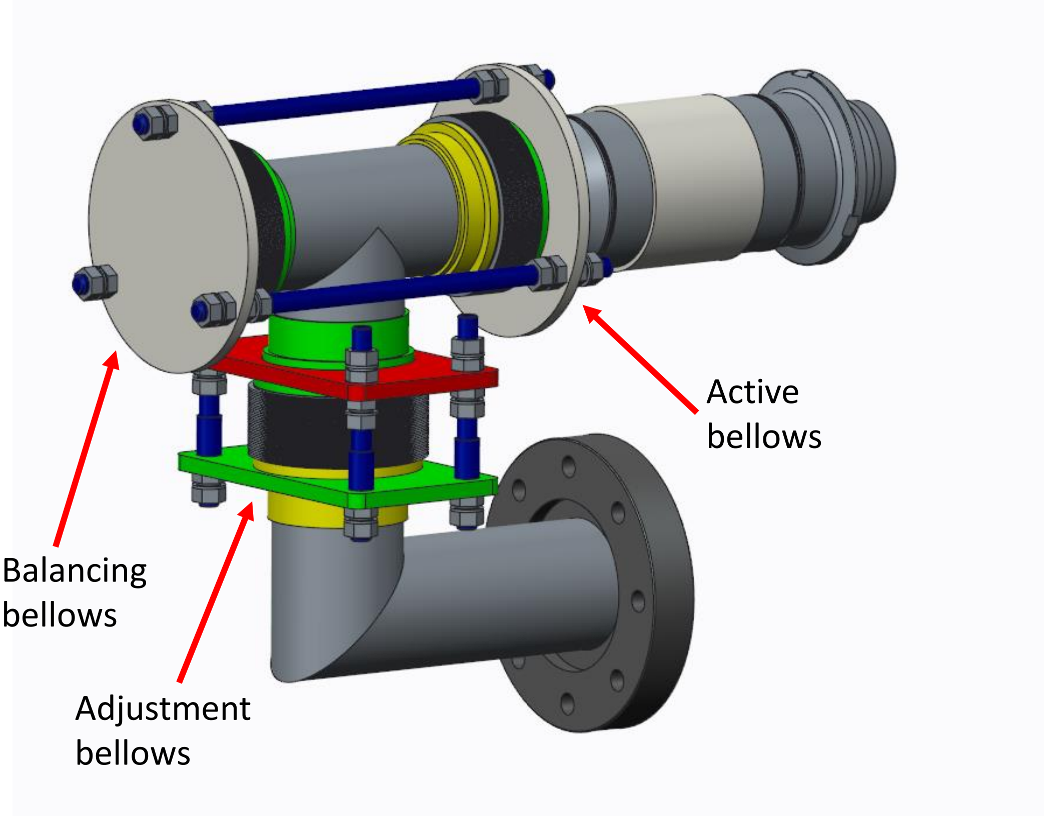


Pressure testing set up of prototype 5 bar pipes

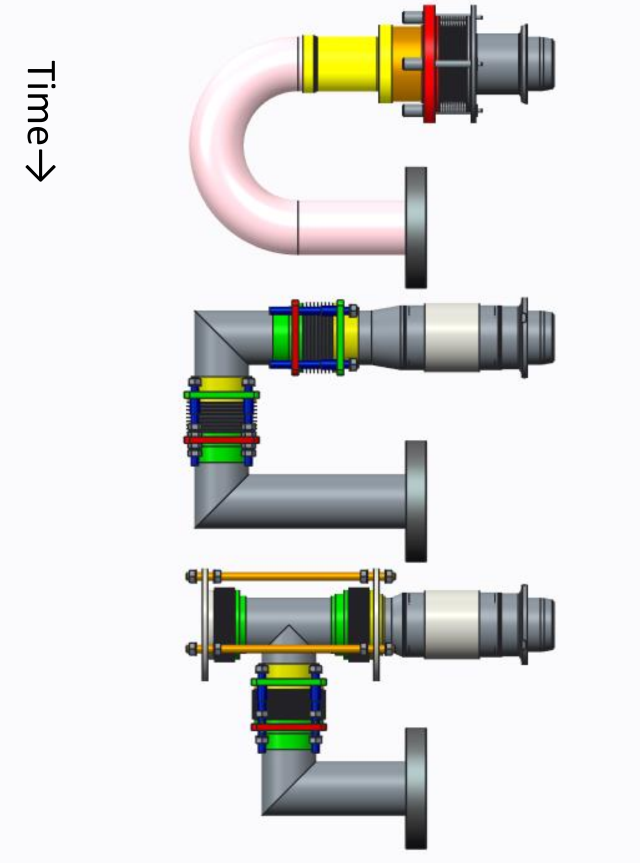
- Integration of a pressure balanced bellows system is necessary
  - Allow compliance for thermal expansion
  - Prevent length growth under internal pressure
- Space is limited and mass/complexity must be kept low
  - Currently in discussion with bellows companies

High Pressure Target Pipes

Potential pressure balanced pipe design:



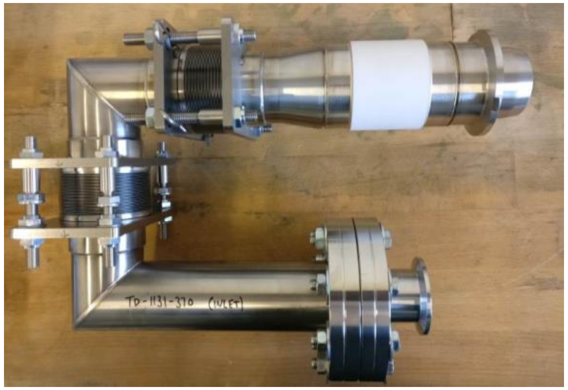
Target Pipe Evolution



Just one reason that target helium pipes are challenging to design and manufacture

Target Ceramics

- Ceramic breaks are a necessity for electrical isolation in all Neutrino facilities (used in target, horn, striplines etc.)
  - Typically Alumina (Al_2O_3) in purities between 90-99.5%
  - They are brittle, fragile and easily broken if loaded in any manner except axial compression
- They feature in several areas for the T2K target:
  - Target mounting
  - Helium cooling pipes
- Ceramic breaks are a potential limiting factor for all Neutrino facilities
  - Commonly see water leaks, gas leaks etc. at joints containing ceramic isolation
- RAL HPT group has investigated several types of isolator for T2K with varying degrees of success
  - Diffusion bonded
  - Bolted
  - Brazed

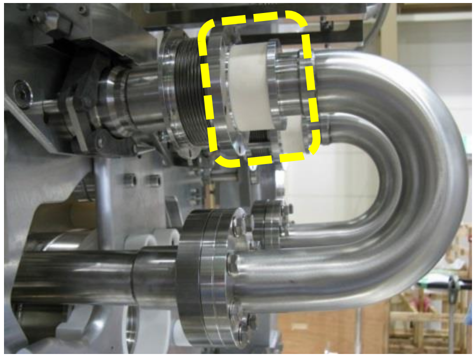


Target helium pipes with brazed alumina isolator for 750kW operation

Target helium pipes with diffusion bonded alumina isolator for 750kW operation

Target Helium Leak

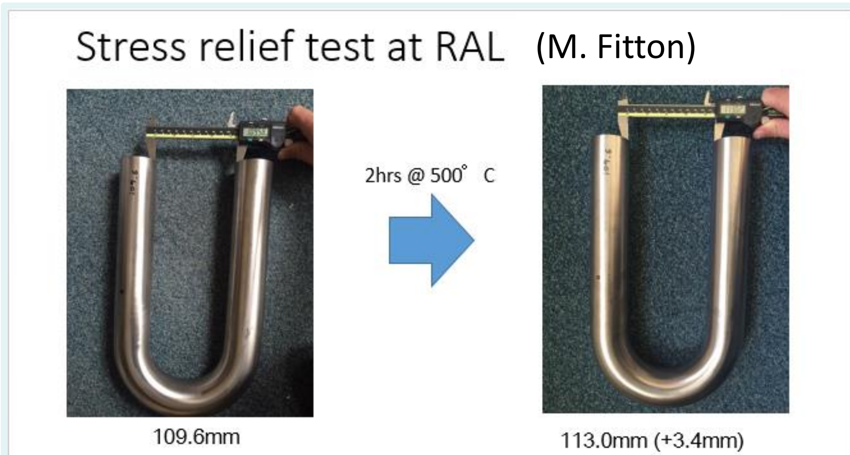
- June 2015: Helium leak detected in target cooling system
- September 2015: Leak investigations in remote maintenance area (RMA) identify leak at ceramic isolator in target helium outlet pipe
- Leaking pipe was replaced remotely with help of TRIUMF in December 2015
- Possible causes:
  - Stress relieving of cold bent stainless pipes?
  - Thermal shock/fatigue due to rapid thermal cycling?



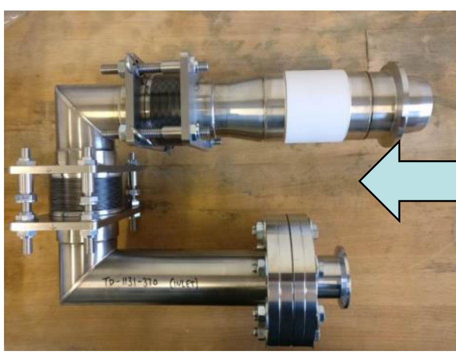
Leak location

Stress Relieving of Bent Pipes

- Pipes tested at RAL opened up by >3mm after furnace run @500°C/2hrs and 200°C/64hrs



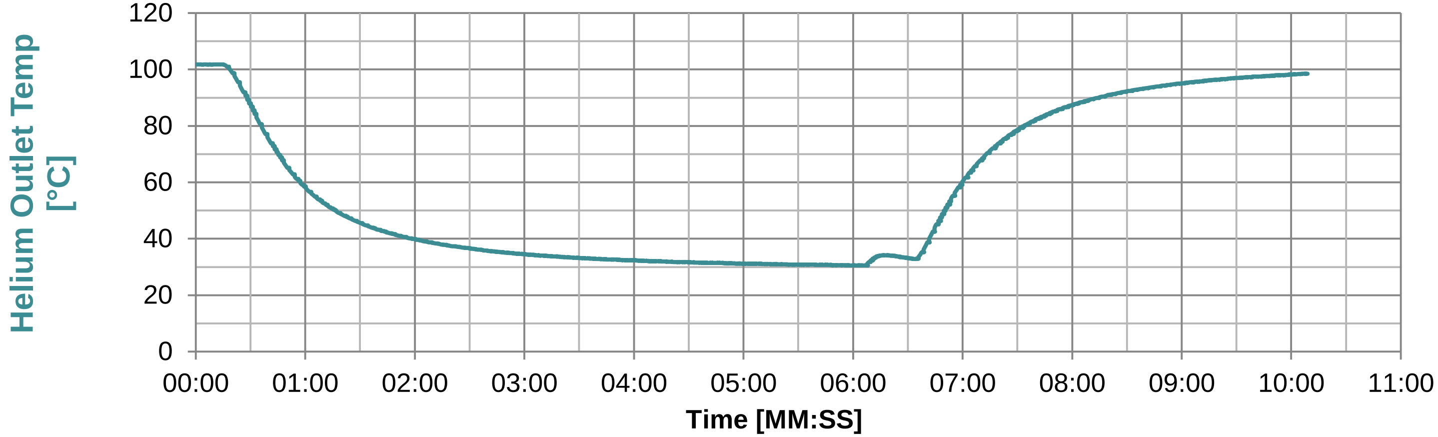
- 3mm lateral movement greater than tolerable by bellows
- Shear/bending put on the ceramic isolator potentially caused failure → gas leak



Outcome:
Welded, mitred pipes (relieved for dimensional stability during manufacture)

Beam Trips – Thermal Shock/Fatigue?

- Beam trips are an inevitability during operation
- Data from operations at JPARC suggest approximately hourly beam trips whilst running
- Heat load is removed from target when the beam trips, but helium flow continues
- Rapid cooling of target helium causes outlet pipes to see rapid thermal cycling during beam trips:



Target helium outlet temperature data from a beam trip at 480kW beam power operation (provided by KEK Neutrino group)

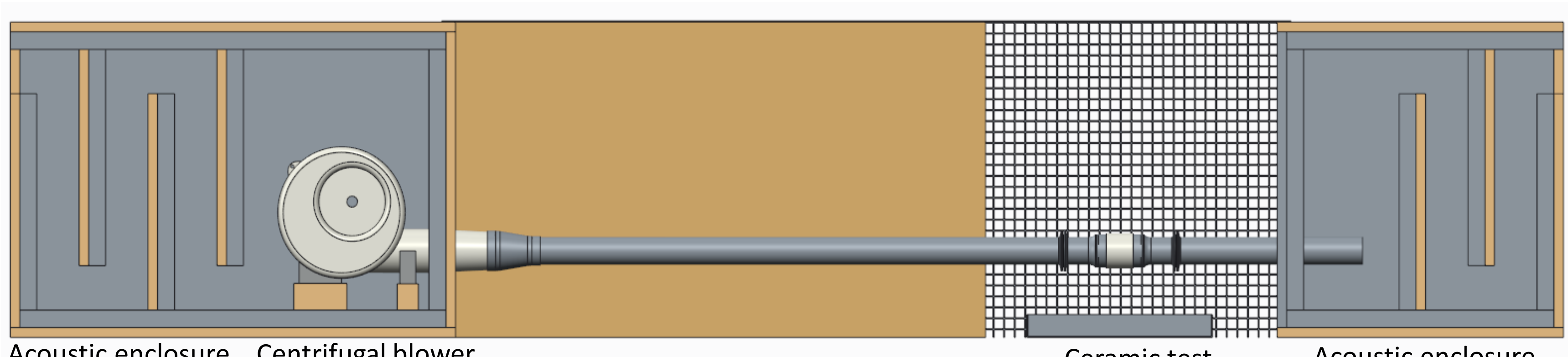
- Outlet He temperature:
  - Drops at a cooling rate of 80°C/minute
  - Rises at a similar rate when the beam goes back on → **thermal shock and thermal cycling on the brittle ceramic isolators**

Hourly trips, 24hr operation, 180 days/year = 5000 thermal cycles per year

→ Offline testing?

Testing – Thermal Cycling

- A test-bed was created at RAL to address the issue of thermal shock/fatigue on target ceramics



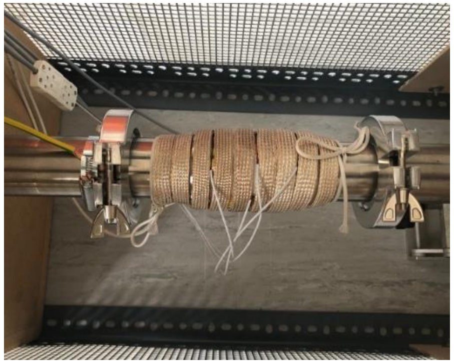
Acoustic enclosure (air inlet)

Centrifugal blower ($600\ m^3/hr$)

Ceramic test section

Acoustic enclosure (air exhaust)

Test section is heated by a 600W heater tape:



HEATING - PID controlled ramp to set point temperature: 200°C @ 36°C/min

SOAK – Soak at 200°C for 3 minutes to eliminate thermal gradients in test section

COOL - Rapid cool w/ blower @ 70°C/min initial rate

Testing – Thermal Cycling

- A test-bed was created at RAL to address the issue of thermal shock/fatigue on target ceramics

	Temperature Range (°C)	Max cooling rate (°C/min)	Max heating rate (°C/min)	Number of cycles completed	Failure detected
Testing Phase 1	40-140	50	36	5120	No
Testing Phase 2	40-160	55	36	5200	No
Testing Phase 3	40-180	60	36	5160	No
Testing Phase 4	40-200	70	36	16118	No

HEATING - PID controlled ramp to set point temperature: 200°C @ 36°C/min

SOAK – Soak at 200°C for 3 minutes to eliminate thermal gradients in test section

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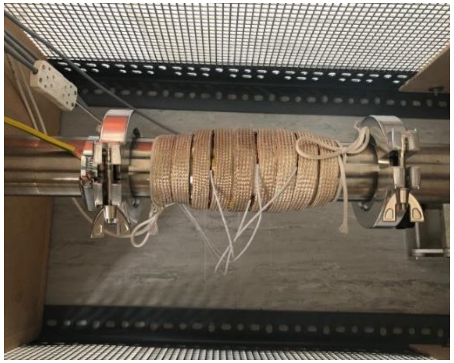

Are test conditions as harsh as operating conditions?

Use operational data (485kW) and extrapolated simulations for higher power

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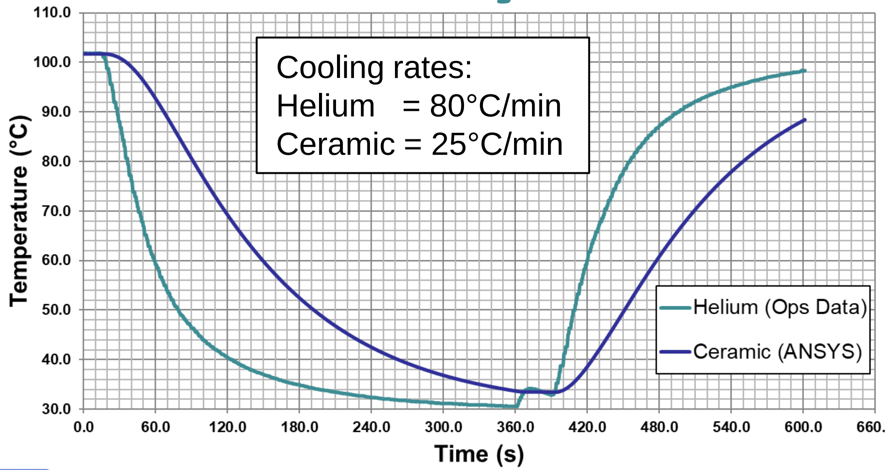
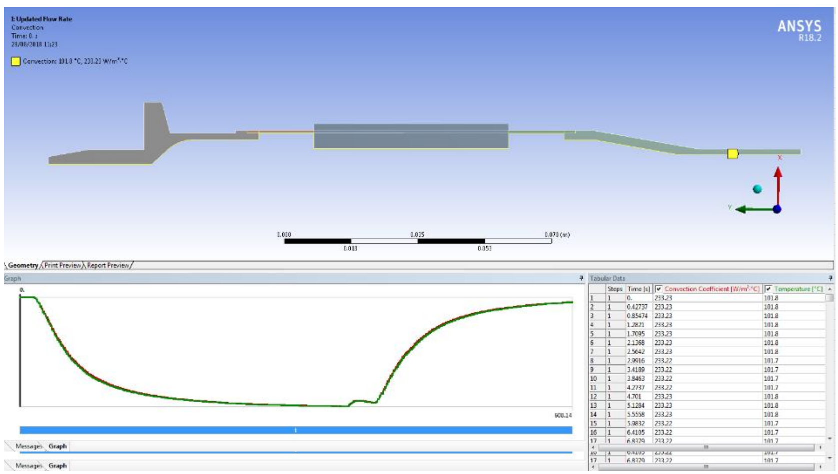
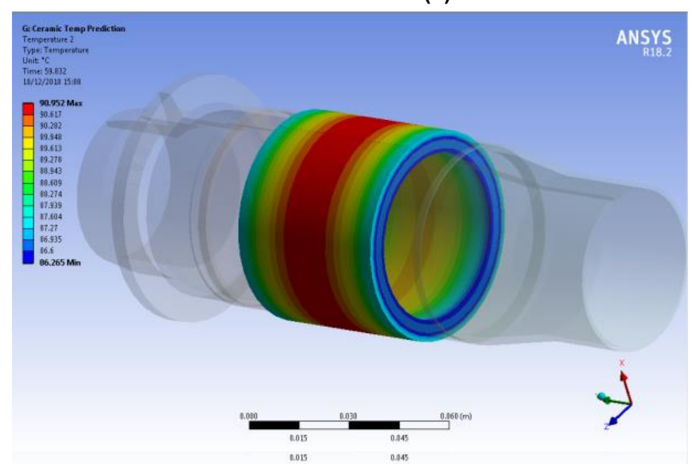
Beam Trips - Thermal Analysis

- 480kW helium beam data used as an input to ANSYS transient thermal analysis
- Temperature at outer surface extracted
  - We can compare this with PT100 location on lab tested ceramics
- Ceramic temperature lags behind helium temperature significantly





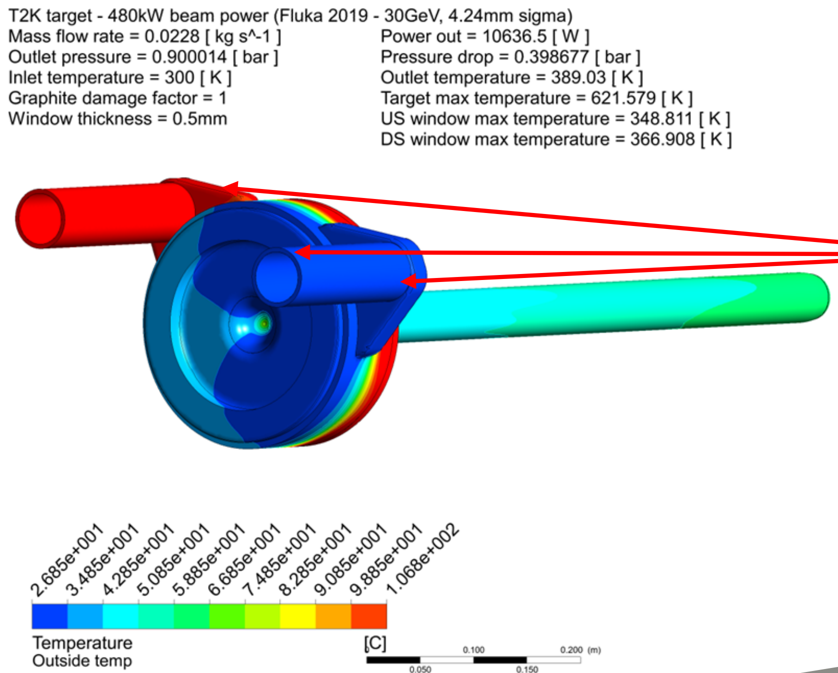


What about cooling rates at higher beam power/helium pressure?

Conjugate heat transfer simulations

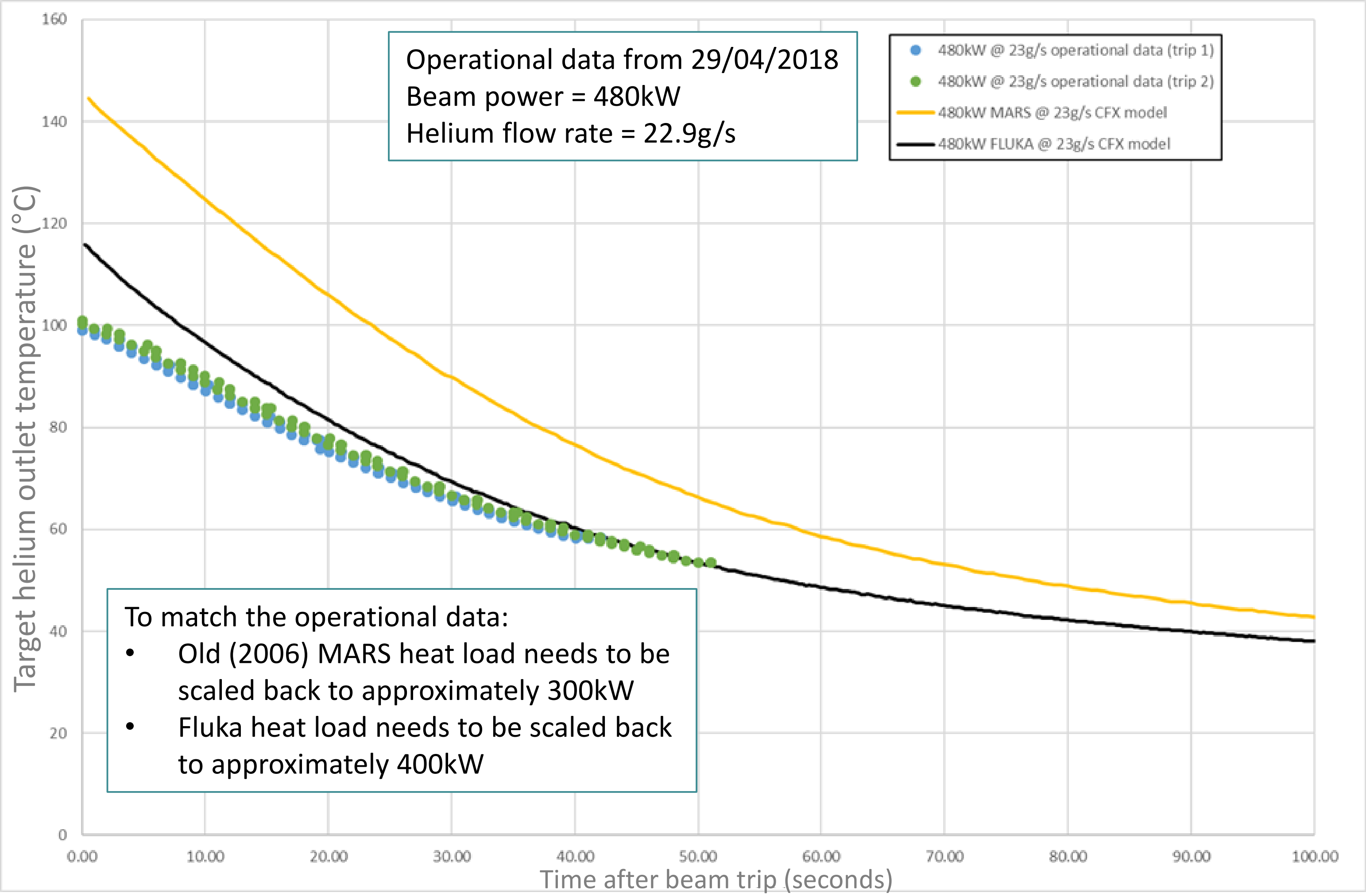
Beam Trip Simulation

- Run steady state conjugate heat transfer model (CFX) of target
  - MARS/Fluka heat inputs
- Import steady state temperatures as input to transient simulation with heat load removed
- Extract helium outlet temperature as a function of time and compare with operational data
- This can be used as:
  - An input to ceramic thermal analyses
  - **Verification of heat deposition calculations using Monte Carlo codes**



Target model includes all material such as outer cover, ears and pipes - thermal mass is important for transient simulation.

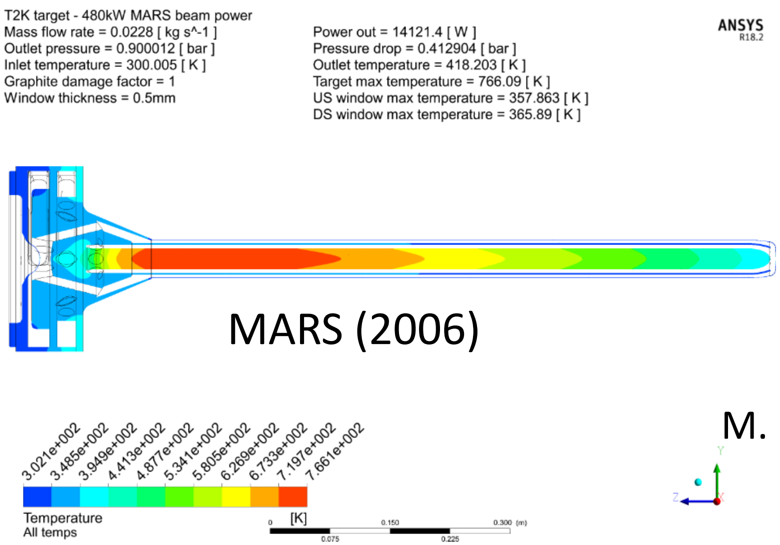
Beam Trips - Operational Data vs Simulations



Heat Load Discrepancy

These simulations have highlighted some significant differences between operational data and the engineering analysis using heat loads from Monte Carlo codes

- 480kW operational data, temp. rise of He = 73.4°C @ 22.9g/s → 8716W
- 480kW MARS (2006), temp. rise of He = 145.2°C @ 22.9g/s → 14,121W (x1.6)
- 480kW FLUKA (2019), temp. rise of He = 89.0°C @ 22.9g/s → 10,636W (x1.2)



MARS (2006)

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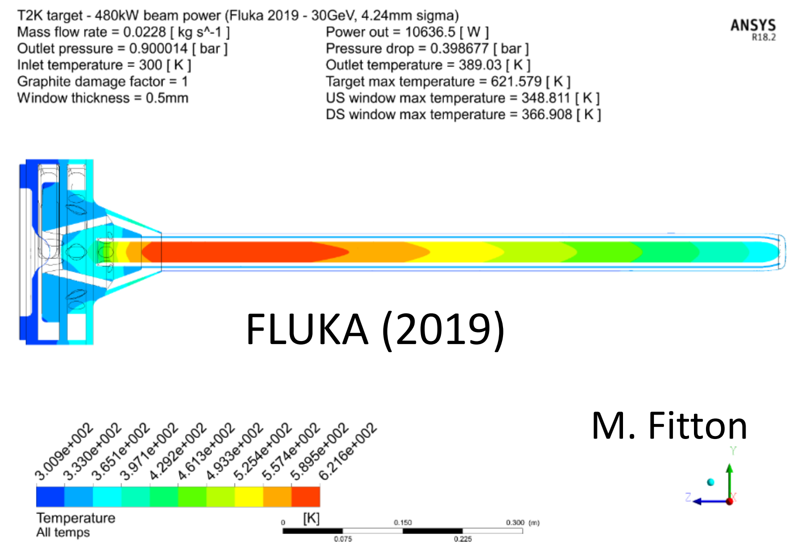

FLUKA (2019)

M. Fitton

This is good news for us as flow rate & pressure for 1.3MW could be reduced

- 4 BarG outlet pressure looks feasible, reduced flow rate study is underway

We are aware that older versions of MARS can predict significantly more heat load than newer versions of MARS and Fluka

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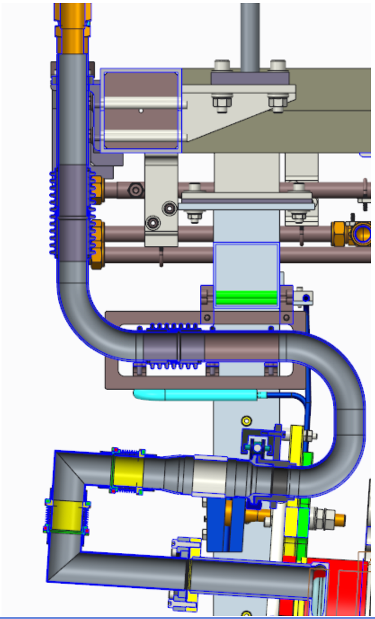
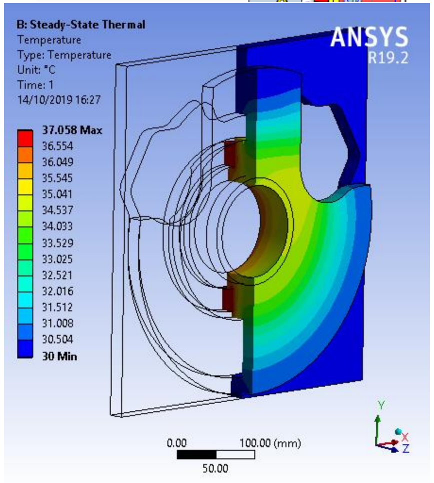
Other Heat Losses

- Heat loss from between target outlet and thermocouple position:
  - Ø50.8mm pipe
  - HTC ~ 10W/m^2.K
  - Ambient helium temperature = 40°C
  - Helium pipe @ target outlet temp = 100°C
  - Pipe surface area/meter = 0.159m^2
  - Power loss = 10 x 0.159m^2 x (100-40) = 63.6W/meter
  - → ***Not significant over the approx. 1.5m between target outlet and thermocouple location (100W)***
- Conduction from target head to target support plates:
  - Target head mounting face is at 37°C
  - TS ambient helium @40°C (negligible heat transfer)
  - Target support plates water cooled, water temperature expected to vary with ambient conditions
  - ANSYS thermal analysis, assuming perfect contact at interfaces:
  - → ***200W heat removed with 20°C cooling water***
  - → ***35W heat flow into the target if cooling water is at 40°C***





Max unaccounted for loss ~300W (<4% target heat load)

Comparison – Ceramic Thermal Testing

	Temperature Range (°C)	Max cooling rate (°C/min)	Max heating rate (°C/min)	Number of cycles completed	Failure detected
480kW @23g/s (Op data - ANSYS)	33-100	25	23		-
1.3MW @32g/s (CFX-ANSYS)	30-167	61	-	-	-
1.3MW @60g/s (CFX-ANSYS)	30-101	53	-	-	-
Testing Phase 4	40-200	70	36	16118	No

Beam data

Linear extrapolation of beam data

- Latest testing phase exceeds estimated operating conditions at 1.3MW for 3+ years operation

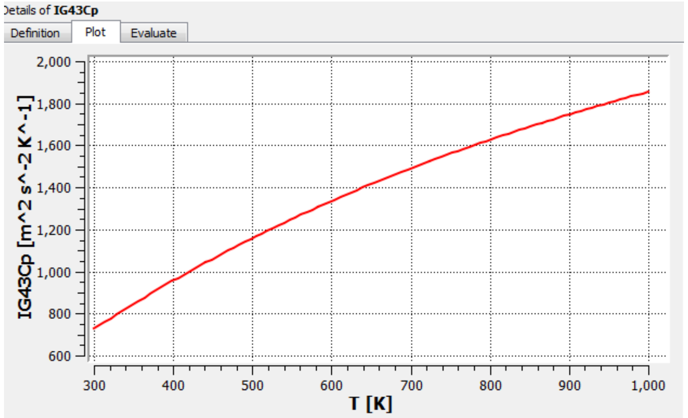
We have good reason to believe that the brazed isolator is suitable for 1.3MW operation

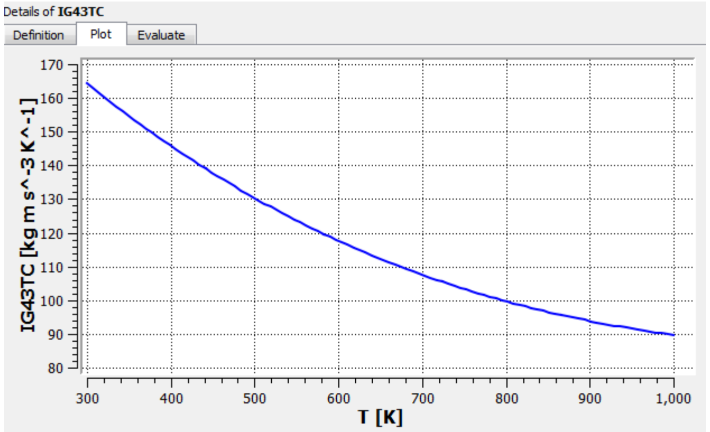
Summary

- Most R&D in order to achieve an operational 1.3MW T2K Target has been completed
- A brazed Alumina isolator has been thermally tested at the equivalent of approximately 3 years running @1.3MW beam power
- Heat loads from MARS and FLUKA codes have been compared to operational data highlighting approximately 40% and 10% respective overestimations of energy deposition in the T2K target
- Key target components have been redesigned for a higher target helium operating pressure of approximately 5 bar
- Prototyping of key components is currently underway

Backup - Simulation Conditions

- Inlet Temperature = 300K
- Fluid = Helium (Ideal Gas)
- Turbulence model = Shear Stress Turbulence (SST)
- Reference pressure = 1atm (Gauge P)
- Target container and window material = Ti-6Al-4V (Gr. 5 Titanium)
  - Specific heat capacity = 526.3 J/kg.K
  - Thermal conductivity = 6.7 W/m.K
- Target material = Toyo Tanso IG-43 (non-linear properties as below)





- Conjugate heat transfer model (coupled CFD-Thermal model)

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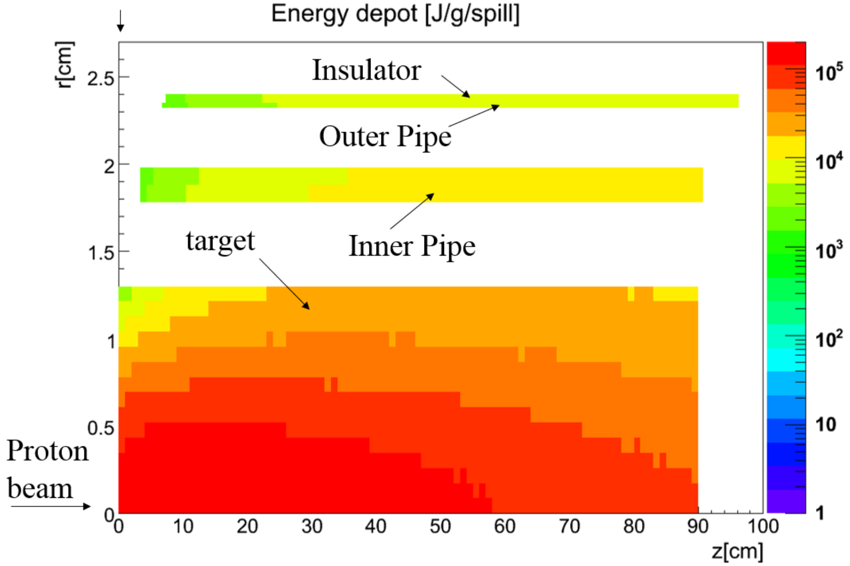
Backup - MARS (2006) heat deposition for target

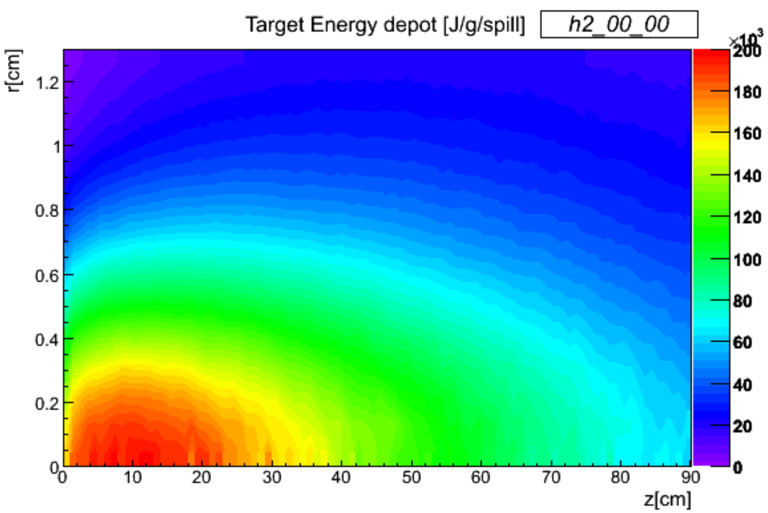


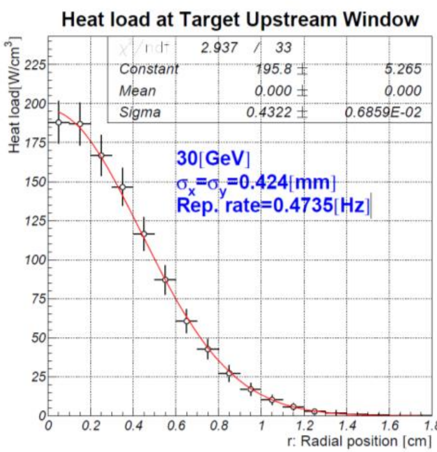
750kW, 3.3e14ppp , 2.11sec

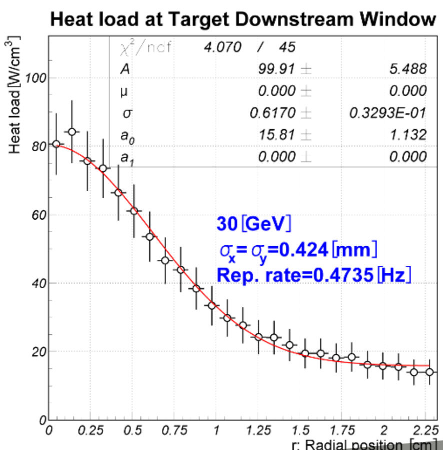
Target core

Peak energy density = 200J/g

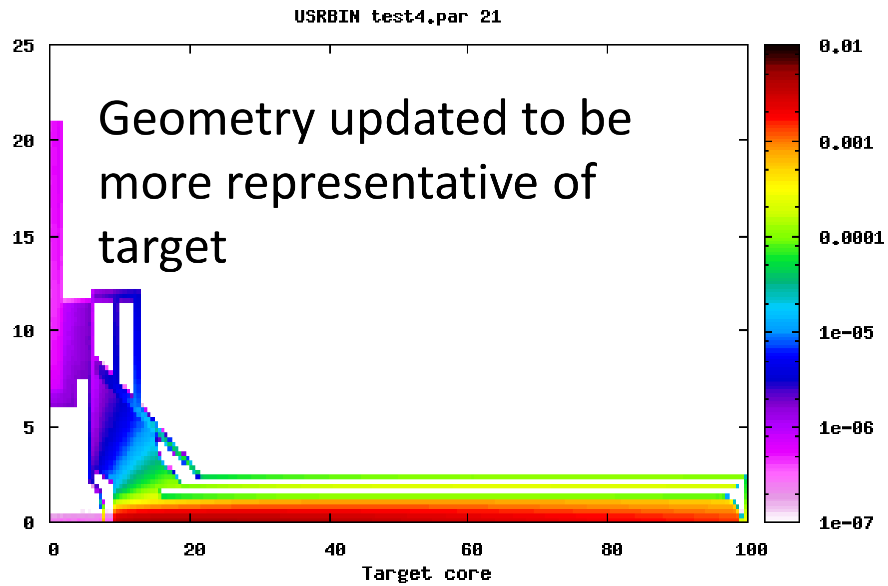
Integrated energy = 39,262J/spill

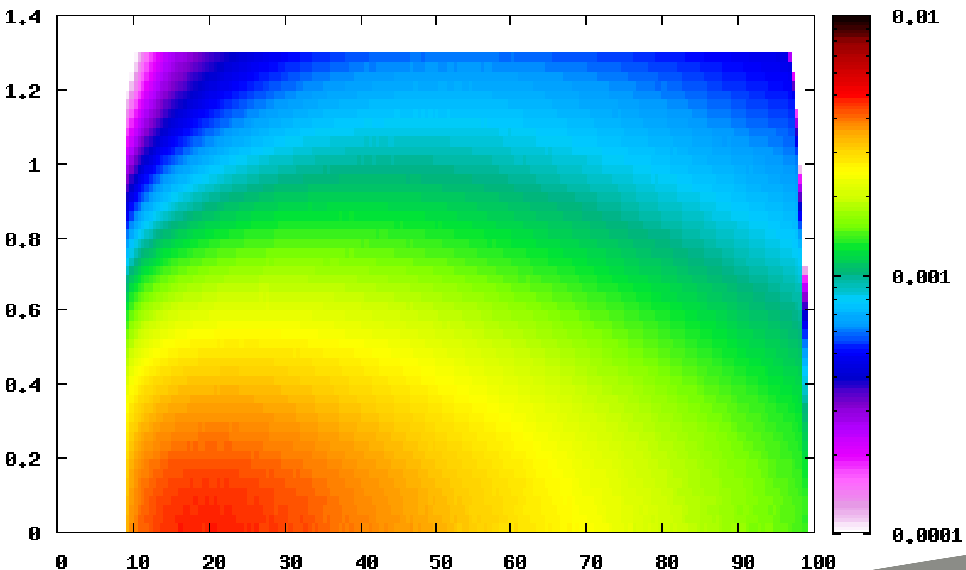






Backup - FLUKA (2019) heat deposition for target





Fluka Flair version: 2.3-0

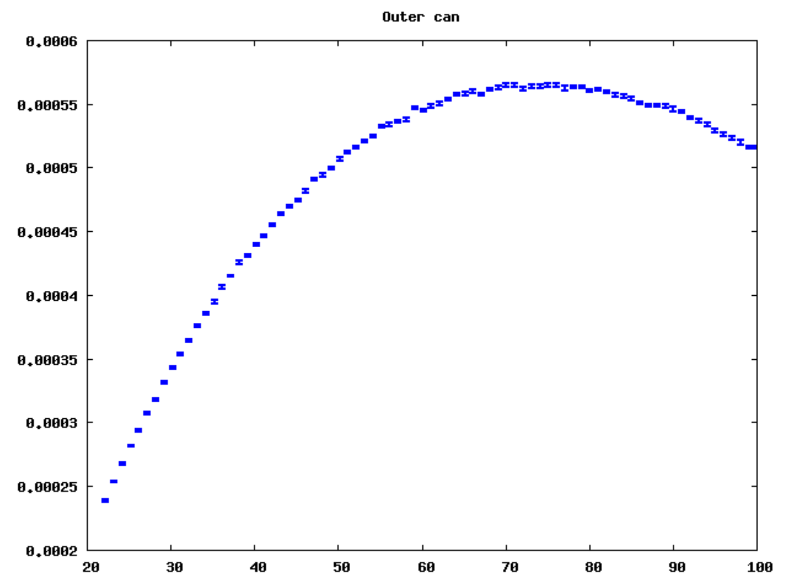
Beam energy: 30GeV

Particle: Proton

Beam shape: 0.999cm FWHM Gaussian

→ 4.24mm Sigma

Number of primaries: 4,000,000



Backup - FLUKA (2019) heat summary

Name	Int	Max
	GeV/primary	GeV/cc/primary
core	0.5680859	4.75E-03
innertube	0.0467516	3.91E-04
outercan	0.0280867	5.67E-04
uswin	0.0043021	7.16E-03
dswin	0.0007273	3.00E-03
head	0.0181921	9.14E-05

T2K achieved operation
480kW @ 30GeV
2.48×10^{14}ppp @ 2.48s

	Int	Max
	W	J/g/spill
core	9,102	102
innertube	749	8
outercan	450	5
uswin	69	64
dswin	12	27
head	291	2
	10,673	

750kW proposed
750kW @ 30GeV
2.0×10^{14}ppp @ 1.32s

	Int	Max
	W	J/g/spill
core	14,202	82
innertube	1,169	7
outercan	702	4
uswin	108	52
dswin	18	22
head	455	2
	16,654	

HK proposed upgrade
1.3MW @ 30GeV
3.2×10^{14}ppp @ 1.16s

	Int	Max
	W	J/g/spill
core	24,617	132
innertube	2,026	11
outercan	1,217	7
uswin	186	82
dswin	32	35
head	788	3
	28,866	

Backup – Mars/Fluka vs Ops Data